

Systematic effects in the estimate of the local gamma-ray emissivity

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We show in this letter that estimates of the local emissivity of γ -rays in the GeV-TeV range suffer uncertainties which are of the same order of magnitude as the current Fermi results. Primary cosmic-ray fluxes, cosmic-ray propagation, interstellar helium abundance and γ -ray production cross-sections all affect the estimate of this quantity. We also show that the so-called nuclear enhancement factor – though widely used so far to model the γ -ray emissivity – is no longer a relevant quantity given the latest measurements of the primary cosmic ray proton and helium spectra.

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INTRODUCTION

The study of the Galactic γ -ray diffuse emission is of utmost importance as this component needs to be subtracted to identify other extended astrophysical sources, such as the extra-galactic background or a possible dark matter component, and also because it is an interesting probe of the cosmic-ray population not only locally, but all over the Galaxy. In Delahaye et al. [9], we have shown how the morphology of the main component of the γ -ray diffuse emission (namely the one due to π^0 decay) is affected by the various uncertainties due to cosmic-ray propagation, gas distribution etc. Here we propose to look more closely into the specific features of the spectrum of this emission, especially in the light of the recent experimental data [1].

The local γ -ray emissivity from π^0 decay has been thoroughly studied by the Fermi collaboration [1] which found that the data are consistent with a high nuclear enhancement factor ϵ_M of 1.84 as found by Mori [17] when considering the cross-section given by Kamae et al. [13]. However we have already seen (see ref [9]) that these data seem to be in tension with the more recent cross-sections by Huang et al. [12].

In this letter we investigate explanations of this discrepancy as well as the various uncertainties affecting the estimate of the γ -ray emissivity. We quantify the impact of the primary cosmic-ray spectra, of their propagation, of the metallicity of the Interstellar medium (ISM) and of the production cross-sections. For this, we follow the method developed in Delahaye et al. [9]. As a reference case, we will consider the primary fluxes by Shikaze et al. [24], the med propagation parameters, a helium to hydrogen ratio of 1/9, and the cross-sections by Kamae et al. [13] with the nuclear weights from Norbury & Townsend [18]. After having defined the various quantities at stake,

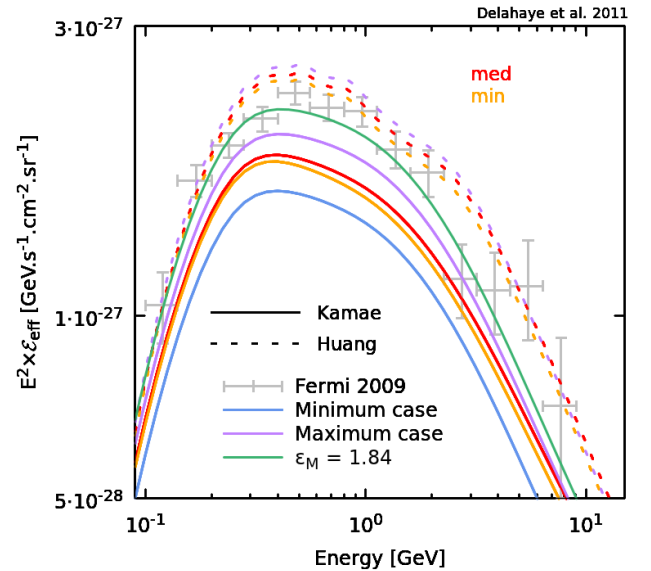


FIG. 1. Effective emissivity as a function of energy. Plain lines correspond to Kamae et al. [13] cross-sections and dashed lines to Huang et al. [12] ones. Red and orange lines are respectively for med and min propagation parameters. The green line corresponds to the Kamae et al. [13] cross-sections used with a nuclear enhancement factor of 1.84 as suggested in the Fermi paper. The blue and purple lines correspond respectively to a minimum and a maximum case which are detailed in the text. Gray points are the recent Fermi data [1]

we vary each parameter one by one to estimate its impact on the γ -ray emissivity and finally conclude.

DEFINITION OF THE QUANTITIES OF INTEREST

The hadronic γ -ray emissivity of an interstellar nucleus A impacted by the cosmic-ray species b is given by the convolution:

$$\mathcal{E}_A^b(\mathbf{x}, E) = \int_{T_{min}}^{+\infty} dT \left\{ \frac{d\sigma}{dE} (b[T] + A \rightarrow \gamma[E]) \times \Phi_b(\mathbf{x}, T) \right\},$$

where $\Phi_b(\mathbf{x}, T)$ is the flux of cosmic ray species b . Because the γ -ray flux is correlated to the hydrogen number density n_H , it is more convenient to use the effective emissivity per hydrogen atom defined as.

$$\mathcal{E}_{eff}(\mathbf{x}, E) = \sum_A \frac{n_A}{n_H} \{ \mathcal{E}_A^p(\mathbf{x}, E) + \mathcal{E}_A^\alpha(\mathbf{x}, E) \}.$$

The Fermi collaboration has selected two intermediate latitude regions in which the hydrogen is atomic and mostly local. The point sources and the inverse Compton component have been subtracted from the maps. The residual flux has been correlated to the HI column density, yielding an effective emissivity $\mathcal{E}_{eff}(E)$ which could be considered a priori equal to the solar value $\mathcal{E}_\odot(E) \equiv \mathcal{E}_{eff}(\mathbf{x}_\odot, E)$. How local is the Fermi measurement is at the center of our analysis. What Fermi actually measures is in fact quite close to the average of the γ -ray emissivity \mathcal{E}_{eff} over the lines of sight of the pixels of the maps. What Fermi actually measures is in fact quite close to the average of the γ -ray emissivity \mathcal{E}_{eff} over the line of sight. That is why we have computed the emissivity inside each pixel by weighing it with the HI spatial density and averaged the results over the sky region investigated in the Fermi analysis.

A quantity commonly used in the literature is the nuclear enhancement factor which is defined as the ratio $\epsilon_M = \mathcal{E}_{eff}(\mathbf{x}, E) / \mathcal{E}_H^p(\mathbf{x}, E)$. The variations of ϵ_M with position \mathbf{x} and energy E have been so far disregarded and the nuclear enhancement factor has been mainly introduced as a constant by which proton-hydrogen interactions have to be renormalized in order to yield the total γ -ray flux. Even at the Sun, it depends on the energy since it can be expressed as

$$\epsilon_M(E) = \sum_A \frac{n_A}{n_H} \left\{ w(1, A) + w(4, A) \frac{\Phi_\alpha(\odot, E)}{\Phi_p(\odot, E)} \right\},$$

where, $w(A_1, A_2)$ are the nuclear weights by which the proton plus proton cross-section is multiplied to get the one of heavier elements collision. Until recently, it was thought that the ratio of α to proton cosmic ray fluxes is constant with energy. However, recent results from [2, 21, 26] indicate that this ratio is increasing at high rigidity. The exact explanation of this increase is still under investigation (see for instance [4]) but has quite an impact on all secondary cosmic ray [11, 14] fluxes. As one

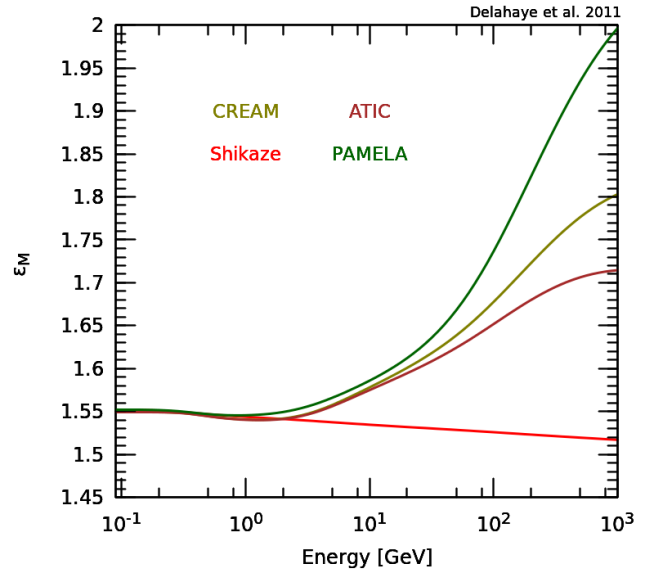


FIG. 2. Nuclear enhancement factor plotted as a function of the energy in the specific case of Kamae et al. [13] cross-sections with nuclear weights from Norbury & Townsend [18]. Other models give similar results. The colored curves correspond to primary cosmic ray fluxes measured by BESS [24], CREAM [26], ATIC [21] and Pamela [2].

can see from Fig. 2, ϵ_M may vary by more than 30% from 1 GeV to 1 TeV making this quantity absolutely useless especially in the case where the fit to the PAMELA data proposed in the appendix are used.

PROPAGATION

As one can see from Fig. 3, in the direction $l \in [-160^\circ; -100^\circ]$, $b \in [22^\circ; 60^\circ]$, which is the direction of interest of the Fermi study, the gas is mainly within 1 kpc from the Sun. However, depending on the propagation parameters chosen, the cosmic ray flux may exhibit a gradient within this 1 kpc. This translates in the fact that \mathcal{E}_{eff} can differ from \mathcal{E}_\odot by up to 10% especially at energies higher than 10 GeV (see Fig. 4).

In the present case, we have taken into account the cosmic-ray propagation within the framework developed in Delahaye et al. [9] making use of the propagation parameters which give a good agreement with all cosmic-ray flux measurements [16, 22]. Within this consistent framework three propagation parameter sets have been singled out [10], they give a relatively good estimate of a median and two extreme cases labeled min, med and max in Figs. 1, 3 and 4. The med set is always used in this work unless specifically written otherwise.

Note however that the gradient of cosmic-ray in the direction of study not only depends on the propagation parameters but also on the cosmic-ray source profile. As one can see in Fig. 4 if we consider the less steep source

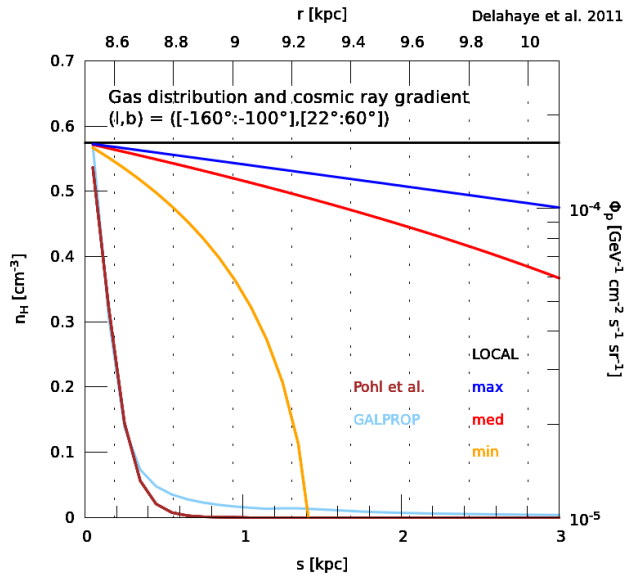


FIG. 3. Gas density (left ordinate) and cosmic ray gradient (right ordinate) as a function of distance from the Sun (lower abscissa) or from the galactic center (upper abscissa).

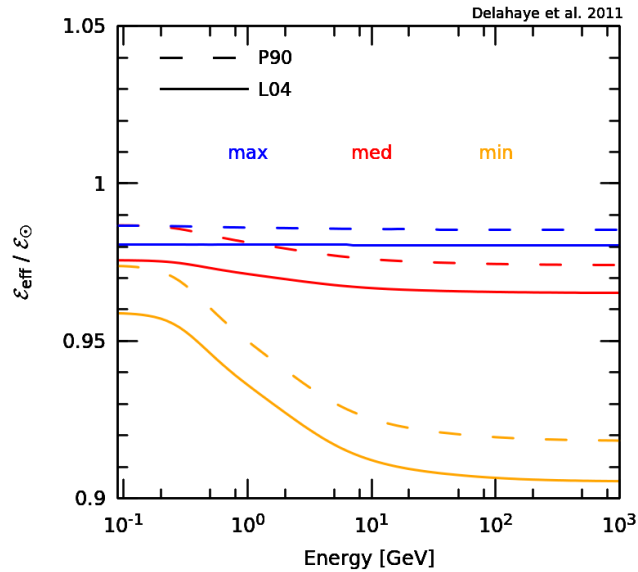


FIG. 4. Effective emissivity divided by solar emissivity as a function of energy. Plain lines correspond to source distributions by Lorimer [15] and dashed lines to the one from Paczynski [20]. Red, orange, and blue lines respectively correspond to med, min, and max propagation parameters sets.

profile by Paczynski [20] rather than the one by Lorimer [15], the effect of propagation is quite reduced.

METALLICITY

The chemical composition of the interstellar medium, and what is more interesting in our case, the relative

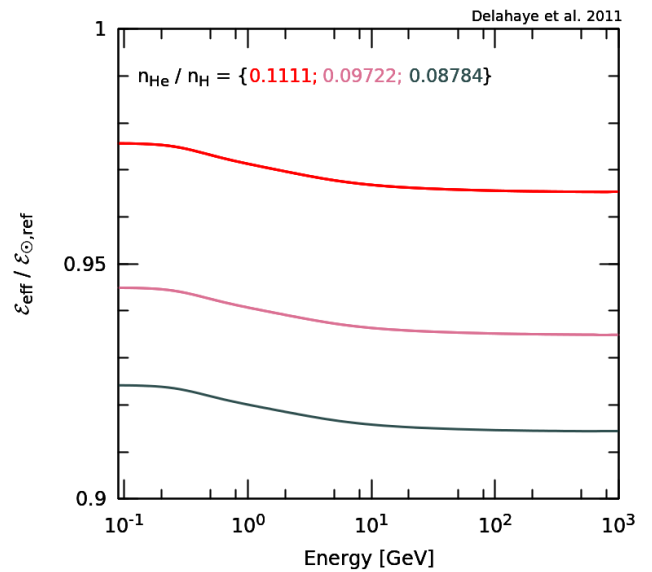


FIG. 5. Effective emissivity divided by solar emissivity as a function of energy. Various values of the helium to hydrogen ratios for the interstellar gas. In red the value considered as a reference in this paper, in pink a value consistent with observation of the local region and in dark green a value consistent with observations of the anti-center.

abundance of helium with respect to hydrogen is not precisely known. The cosmological value is about 0.077 He atom per H [19] however, due to stellar evolution, the metallicity has evolved in the Milky Way. Because the stars do not have the same mass and age everywhere in the Galaxy, one should expect to have a helium gradient decreasing from the Galactic Center towards the outside regions. This is indeed supported by various observations [5, 8] and theoretical models [6]. On average one can consider that $n_{\text{He}}/n_{\text{H}}$ varies from ~ 0.111 at the Galactic Center to ~ 0.087 in the outer region with a local value of ~ 0.097 . These three values are illustrated in Fig. 5. The reason why we have considered a high metallicity as a reference model is only because it was the value taken by Huang et al. [12], allowing easier comparisons.

The $p+\text{He}$ process and the $\alpha+\text{He}$ one amount respectively for $\sim 20\%$ and $\sim 5\%$ of the total signal hence varying $n_{\text{He}}/n_{\text{H}}$ by 20% translates in a variation of the total signal of 5%, as one can see from Fig. 5.

CROSS-SECTIONS

As a reference case (hereafter called KNT) we considered the cross-sections by Kamae et al. [13] (based on PYTHIA 6 [25]) with the nuclear weights from Norbury & Townsend [18]. Huang et al. [12] (but also Mori [17], which lead to the value of $\epsilon_M = 1.86$) is based on DPMJET3 [23]. Both these Monte Carlo generators were not tuned with TeVatron and LHC data at the time of

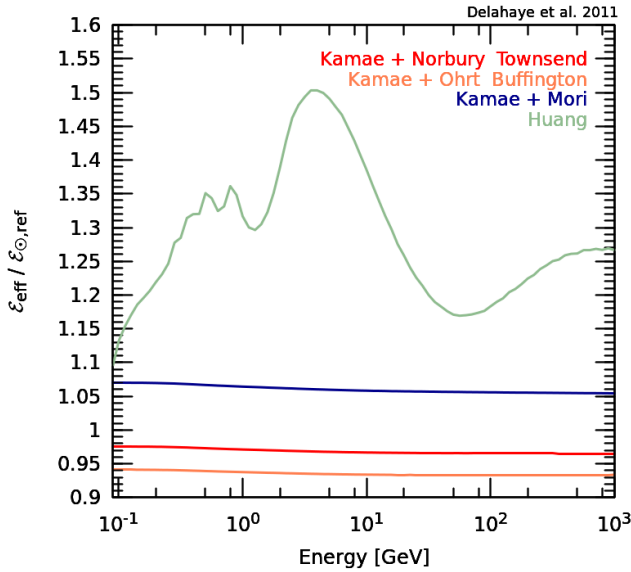


FIG. 6. Effective emissivity divided by the reference solar emissivity (KNT) changing cross-sections and nuclear weights.

these works hence it is probable that one may expect some change in the future. Though Cholis et al. [7] have shown that taking into account more recent versions of **PYTHIA** does not change much the results.

However, considering what is available for the moment, as one can see in Fig. 6, the different models of nuclear weights and cross-sections have a large impact on the estimate of the γ -ray emissivity. In the case of the production cross-sections of Huang et al. [12], the difference reaches 50%. Note that the tables available concern cross-sections of cosmic-ray protons and α which interact with a mixture of hydrogen and helium but also carbon, nitrogen and oxygen. It is hence not possible to change these proportion and it is hard to tell whether the differences come from the interstellar medium metallicity or from the Monte-Carlo.

The sharp features of the green line of Fig. 6 are due to the resonances that Huang et al. [12] have added to their cross-sections.

CONCLUSION

The various effects we have pointed out in this letter: primary cosmic-ray fluxes, propagation, and metallicity which lead to uncertainties of order 45%, 10% and 5% respectively are illustrated in Fig. 1 in the KNT case by the blue and purple lines which show the two extreme cases. On top of that, we have also considered the uncertainties due to γ -ray production cross-sections and nuclear weights which vary from 10% to 50%, depending on the energy. Hence the total theoretical uncertainty on the

γ -ray production by π^0 decay is far from negligible.

The statistical uncertainties of the Fermi results vary from $\sim 4\%$ to $\sim 30\%$ which is of the same order than all the effects we have discussed here. Moreover, the Fermi data stop at 10 GeV whereas most models sensibly differ from each other at higher energies. It will hence be of great interest to have more data in the coming years. However, improving the experimental precision calls theoreticians to produce as much an effort to reduce the theoretical uncertainties we have pointed here.

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Fit to the Pamela data

In order to do the computations we mainly used the fit performed by [24] over the BESS data but also the

fit done by Lavallo [14] over data from ATIC [21] and CREAM [3] balloons. Moreover, we propose here a fit to the recent PAMELA data [2]: after demodulating in the force field approximation with a Fisk potential of 500MV:

$$\Phi_p(T) = 35.3 \cdot 10^{-4} \left(1 - \exp \left(- \left(\frac{T}{2.5 \text{ GeV}} \right)^{0.9} \right) \right) \left(\frac{T}{10 \text{ GeV}} \right)^{-2.5} \\ \times \left(1 + \frac{T}{16 \text{ GeV}} \right)^{-0.5} \left(1 + \frac{T}{300 \text{ GeV}} \right)^{0.46} \left(1 + \frac{T}{5 \text{ TeV}} \right)^{-0.21},$$

and

$$\Phi_\alpha(T) = 1.5 \times 10^{-5} \left(\frac{R}{50 \text{ GV}} \right)^{-2.7} \left(1 + \frac{R}{250 \text{ GV}} \right)^{-1.3} \\ \times \left(1 + \frac{R}{1 \text{ TV}} \right)^{5.4} \left(1 + \frac{R}{2 \text{ TV}} \right)^{-4.15},$$

where R stands for the rigidity of the particle and both fluxes are expressed in $((\text{GeV/n}).\text{s.sr.cm}^2)^{-1}$.